

# First Evaluation of Dynamic Aperture at Injection for FCC-hh<sup>\*</sup>

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## Abstract

In the Hadron machine option, proposed in the context of the Future Circular Colliders (FCC) study, the dipole field quality is expected to play an important role, as in the LHC. A preliminary evaluation of the field quality of dipoles, based on the Nb<sub>3</sub>Sn technology, has been provided by the magnet group. The effect of these field imperfections on the dynamic aperture, using the present lattice design, is presented and first tolerances on the b<sub>3</sub> and b<sub>5</sub> multipole components are evaluated.

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## I. INTRODUCTION

The main dipole magnets are critical elements for the machine performance in the case of LHC and of FCC-hh. In particular their field quality impacts the long term stability of the particles in the machine. The behavior of the particles in presence of magnet imperfections cannot be cured by dedicated feedback, therefore, it is important to know them in advance and to correct them if they reduce, below the safety limit, the Dynamic Aperture (DA) of the machine, defined as the region in phase space where stable motion occurs. As in the LHC also in the FCC-hh different magnets are expected to play a role in the definition of the DA at injection and at collision energy. At injection the main dipole field quality is the major contributor to the reduction of DA in LHC [1], while at collision the triplet field quality and the beam-beam effects are the major sources of the DA reduction [2]. The baseline injection energy for FCC-hh has been fixed at 3.3 TeV, which gives more or less the same ratio between injection and collision energy as in the LHC. In the following we discuss the first estimate of main dipole field quality and magnet specifications, using DA as figure of merit. The optics used for this study are briefly introduced in section II. In section III the first estimate of dipole field quality together with the arc magnets specifications are presented. The first evaluation of tolerances on  $b_3$  and  $b_5$  using dynamic aperture and detuning with amplitude and momentum are reported in section IV and V. Finally, possible improvements of these tolerances estimations are qualitatively analyzed in section VI.

## II. OPTICS

The current layout of the FCC-hh ring (see Fig. 1) is made of 4 short arcs (SAR), 4 long arcs (LAR), 6 long straight sections (LSS) and 2 extended straight sections (ESS). The main ring parameters and the main functionality of each of the insertions are reported in [3]. We have considered different versions of insertion optics for the Interaction Region (IR) and the momentum collimation, as far as they became available, while keeping the same arc, injection, extraction and betatron collimation optics.

Three versions of the IR insertion optics have been considered. The first version has been designed with a  $L^*$  of 36 m [4], a  $\beta^*$  of 3.5 m is used for the study of DA at injection and the ultimate  $\beta^*$  of 0.3 m at collision (in the following called v2). In the second version

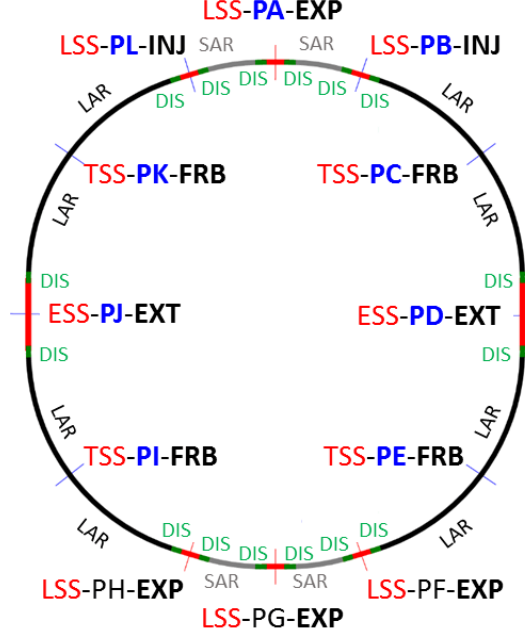


FIG. 1: Present layout of FCC-hh ring.

of the IR optics the  $\beta^*$  value at injection has been increased to 4.6 m to ensure that the aperture bottleneck, and as a consequence the collimation settings, are dominated by the arcs and not the IRs (in the following called v4). Finally, the third version of the IR has been designed with a  $L^*$  of 45 m, due to experimental detector constraints (in the following called v5 [5]). Figure 2 shows the optics function of IR v4 at injection and of IR v5 at

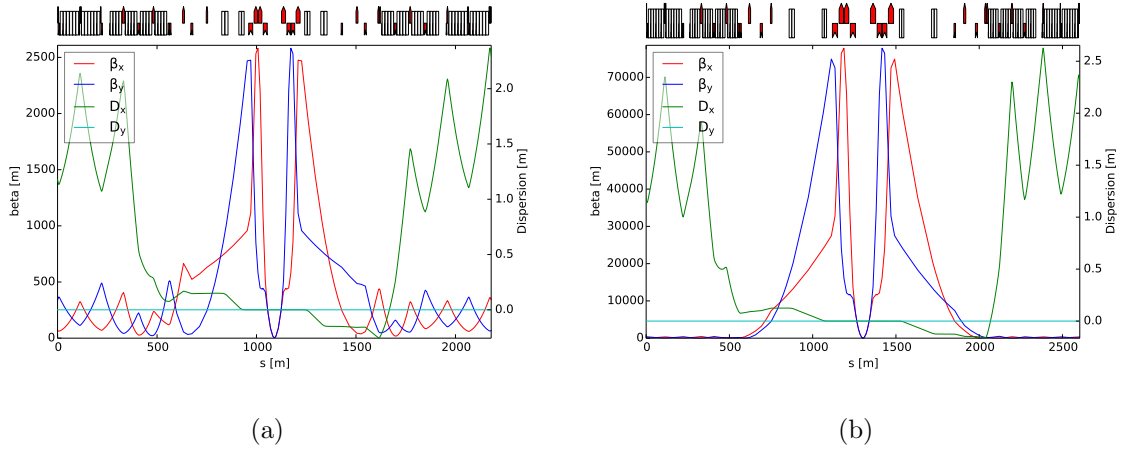


FIG. 2: Interaction Region optics at injection v4, with  $L^*$  36 m and  $\beta^*$  4.6 m (a). Interaction Region optics at collision v5, with  $L^*$  45 m and  $\beta^*$  0.3 m (b).

collision. In the IR v4 and v5 the phase advance between the IPs A and G and the first focusing/defocusing sextupole of the SAR is respectively adjusted to  $90^\circ$  modulo  $180^\circ$  in the horizontal/vertical plane. In all optics versions, the first order chromaticity is corrected ( $Q' = 2$ ) by two sextupole families distributed in the SAR and LAR.

Three versions have been used for the momentum collimation optics, as well: the first two are slightly different versions of simple FODO cells, which have a maximum dispersion of 5 and 4 meters (called fodo90 v1 and fodo90 v2, respectively). The third version of the optics has been designed by scaling the betatron functions and the lengths from the LHC, using the factor  $k = \sqrt{\frac{50}{7}}$  (ratio between the nominal beam energy of FCC and of LHC). A number of FODO cells with  $90^\circ$  phase advance has been added downstream to fill the 4.2 km foreseen for the ESS insertion region (in the following called lhc v1). The concept of the injection and extraction insertions can be found in [6], [7], and the present betatron collimation design is described in [8].

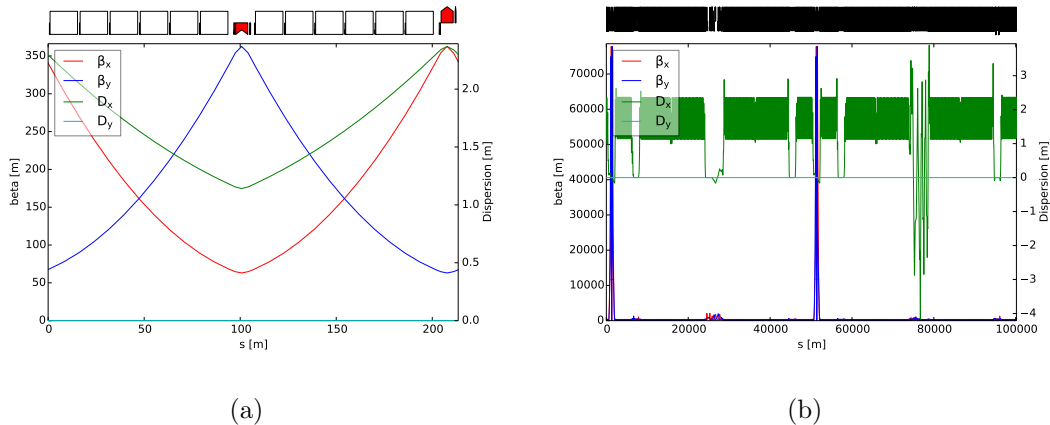


FIG. 3: Optics functions of the Arc FODO cell (a) and the whole ring for FCC-hh (b).

The FODO cells of the arcs are optimized to have the largest filling ratio [9], [10] (Fig. 3 (a)). The phase advance in the FODO cells is exactly  $90^\circ$  in the SAR whereas it is  $90^\circ \pm \epsilon_{x,y}$  in the LAR. The value of  $\epsilon_{x,y}$  is adjusted to tune the whole ring. In particular for the optics considered in this study the value of  $\epsilon_{x,y}$  changes up to  $1^\circ$ , according to the IR and momentum collimation optics version. A dipole is removed at the middle of the LAR to save some space for the technical straight sections (TSS). The optics of the whole ring is shown in Fig. 3 (b).

### III. DIPOLE FIELD QUALITY AND MAGNETS SPECIFICATIONS

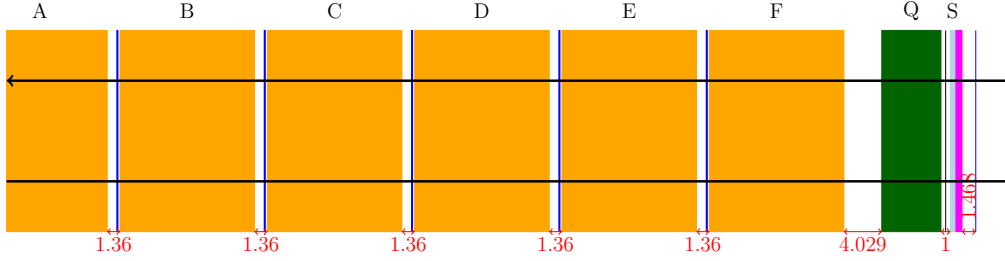


FIG. 4: Arc half-cell layout.

Currently the total arc cell length is  $\sim 214$  m with 12 dipoles and 12 spool pieces for the correction of the  $b_3$  component of the main dipole, one attached to each dipole of the cell (as shown in Fig.4). Both the dipole and the spool piece correctors have the same length of the LHC corresponding magnets. The same interconnection lengths between two dipoles, and between the main dipole and the main quadrupoles have been estimated to be feasible by the magnet group [11]. Octupoles for Landau damping and octupole or decapole correctors are not included in the current version of the lattice layout, neither are skew sextupoles. The dipoles are set at almost their maximum strength (16 T). At this field and at a reference radius of 17 mm a first estimate of the expected field quality for the injection and the collision energy has been provided by the magnets group [11], as shown in Table I.

As in the LHC case [12], the magnetic field expansion used for the magnets reads [13]:

$$B_y + iB_x = B_{ref} \sum_{n=1}^{\infty} (b_n + ia_n) \left( \frac{x + iy}{R_{ref}} \right)^{n-1} \quad (1)$$

where  $B_{ref}$  represent the magnetic field at the reference radius  $R_{ref}$ , for the principal harmonics. The subscript  $n = 1$  refers to dipole,  $n = 2$  to a quadrupole and so on. Each multipole harmonics entering in the dipole field expansion ( $a_n$  and  $b_n$ ) is modeled as the sum of three contributions:

$$b_n = b_{n_S} + \frac{\xi_U}{1.5} b_{n_U} + \xi_R b_{n_R} \quad (2)$$

where  $\xi_U$  and  $\xi_R$  denote the random numbers with Gaussian distribution truncated at 1.5 and 3  $\sigma$ , respectively.

TABLE I: Multipoles used for the main dipole field quality. The values are in units of  $10^{-4}$  at  $R_{ref}=17$  mm.

systematic			uncertainty random	
Normal	inj $b_{n_S}$	col $b_{n_S}$	$b_{n_U}$	$b_{n_R}$
3	-5	20	0.781	0.781
4	0	0	0.065	0.065
5	-1	-1.5	0.074	0.074
6	0	0	0.009	0.009
7	-0.5	1.3	0.016	0.016
8	0	0	0.001	0.001
9	-0.1	0.05	0.002	0.002
Skew	$a_{n_S}$	$a_{n_S}$	$a_{n_U}$	$a_{n_R}$
3	0	0	0.256	0.256
4	0	0	0.252	0.252
5	0	0	0.05	0.05
6	0	0	0.04	0.04
7	0	0	0.007	0.007
8	0	0	0.007	0.007
9	0	0	0.002	0.002
10	0	0	0.001	0.001

The  $b_3$  harmonics of the dipole field is corrected by the spool pieces. In order to have the same specification for the  $b_{3_S}$  component ( $\leq 3$  units) as calculated for LHC in Ref. [14], the maximum strength of the spool pieces correctors required is two times the LHC strength value. With present technology, is possible to obtain a gradient of 4430 T/m<sup>2</sup> (which is 3 times the LHC strength) for a magnet with the same length as the LHC one (0.11 m) [11]. This ensures the possibility to correct up to 6 units of the systematic  $b_3$  component in the main dipoles at collision energy.

The maximum strength used for the main quadrupole of the arcs is equivalent to a field gradient of 360 T/m over a 6.3 meter-long magnet. A first study of the main quadrupole design shows that a 400 T/m gradient is possible over a 6 m long magnet [11, 15].

For the orbit correctors, current technology is able to provide up to 4 T for a 1 meter-long magnet, which seems to be enough given the first evaluation of orbit correction and misalignment tolerances (see ref. [16] for details). The only concern, so far, is the required strength of the sextupoles for the ultimate  $\beta^*$  of 0.3 m, in fact with the present technology a gradient of 5560 T/m<sup>2</sup> over a magnet length of 0.37 m is feasible, therefore a gradient of  $\sim 16000$  T/m<sup>2</sup> can be obtained over a magnetic length of 1.2 m [11]. This leaves no margin for reducing  $\beta^*$ , unless special chromaticity correction schemes are considered.

The main specifications of all the magnets, as agreed with magnets group, are summarized in Table II.

TABLE II: Arc magnets specifications.

<b>magnet</b>	<b>magnetic length [m]</b>	<b>max strength</b>	<b>unit</b>
dipole	14.3	16	T
spool pieces	0.11	4430	T/m <sup>2</sup>
quadrupole	6.0	400	T/m
sextupole	1.2	16059.	T/m <sup>2</sup>
orbit corrector	1.0	4	Tm
dipole-dipole spacing	1.36		m
quadrupole-dipole spacing	>3.67		m

#### IV. DYNAMIC APERTURE

In this section we analyze the impact of the main dipole field errors, reported in Table I, on the long term stability of the machine (DA). The DA has been computed simulating the particles motion over  $10^5$  turns, using a set of initial conditions distributed on a polar grid, in such a way to have 30 particles (different initial conditions) for each interval of  $2\sigma$  in a range from 2 to 40. Five different phase space angles have been used: 15°, 30°, 45°, 60° and 75°. Moreover, in all tracking simulations the fractional parts of the tunes have been fixed to .28 and .31 at injection and to .31 and .32 at collision, as for LHC upgrade in luminosity. Misalignment errors are not included in order to evaluate the effect of the multipole errors alone, as also been done in [1]. As far as the dipole field imperfections are concerned, sixty

different machines (also called seeds) have been generated, using Eq. (2). The  $\xi_U$  random number is kept constant for all the dipoles of the same arc, while  $\xi_R$  changes for each dipole. The momentum offset is set to  $7.5 \times 10^{-4}$  and  $2.7 \times 10^{-4}$  at the injection and at collision energy, same as the LHC, respectively. The normalized *r.m.s.* beam emittance is kept to  $\varepsilon_n = 2.2 \mu\text{m}$  for both the injection and collision energy (3.3 TeV and 50 TeV). In the following, we discuss the results of DA computation at collision first and at injection after.

### A. Collision

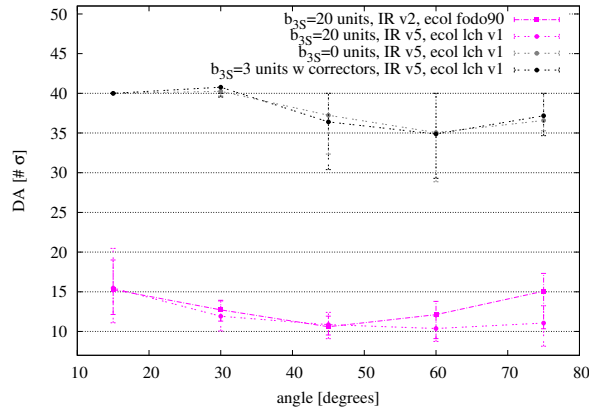


FIG. 5: Dynamic Aperture (DA) at the collision energy of 50 TeV in number of *r.m.s.* beam sizes as a function of the initial phase space angles, see text for details.

At collision energy, for the ultimate  $\beta^*$  value of 0.3 m the minimum DA without any magnet imperfections is above  $54\sigma$ , with minimum values at  $30 - 45^\circ$ . When the dipole field imperfections of Table I are included in the simulations, the DA drastically drops with a minimum DA value of less than  $10\sigma$ , as shown in Fig. 5. This is mainly due to the geometric aberrations induced by the 20 units of  $b_{3s}$  as shown by the grey dots in Fig. 5, where the  $b_{3s}$  value is set to 0. Moreover, the main sextupole strengths required to correct the chromatic aberrations induced by this  $b_{3s}$  are a factor 4 out of the reach of present technology. In order to ensure that the arcs have a small impact on the DA at collision (which is already greatly reduced by triplet imperfections [17] and beam-beam) it is important to fully correct the  $b_{3s}$ . Furthermore, given the maximum integrated strength reachable by the spool piece



correctors, the maximum amount of  $b_3$  we can correct is  $\sim 6$  units (as discussed in previous section). The black dots in Fig. 5 show the perfect compensation of the chromatic and geometric aberrations due to 3 units of  $b_{3s}$  at collision. The average  $b_3$  of each of the 8 arcs is corrected by the 12 spool pieces attached to each of the main dipoles. About 54% of the maximum strength of the spool pieces is used to correct the 3 units of  $b_{3s}$ . A maximum value of 3 units is assigned as target value for  $b_{3s}$ , which (according to the magnet group) seems to be feasible if up to 7 units of  $b_{3s}$  are allowed at injection [11]. The different optics versions considered does not change significantly the DA at collision, as shown by comparing the pink dots and squares in Fig. 5.

### B. Injection

At injection, without dipole imperfections the DA is above  $80\sigma$  for each angle explored. As far as the main dipole field imperfections are considered in the tracking simulations the minimum DA reduces to  $14\sigma$ , as shown by the blue dots and squares in Fig. 6.

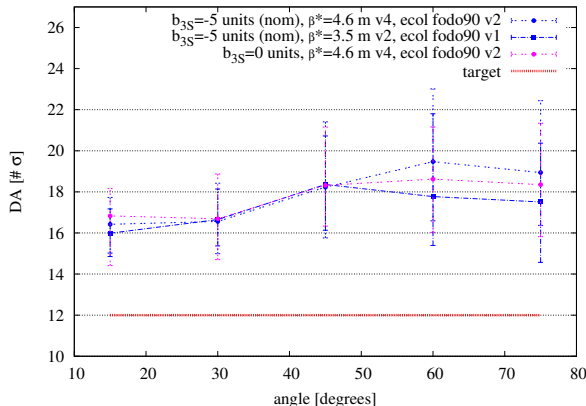


FIG. 6: Dynamic Aperture (DA) at the injection energy of 3.3 TeV in number of *r.m.s.* beam sizes as a function of the initial phase space angles, see text for details.

In these simulations, the geometric aberrations induced by the sextupole component of the dipole field are not corrected, while the chromatic aberrations, induced by the  $b_3$  harmonics of the dipoles, are corrected using the main sextupoles of the arcs. The minimum DA is above the target value of  $12\sigma$  (safety margin adopted for the LHC design). Moreover, by

comparing the blue dots and squares in Fig. 6 with the pink dots, where the systematic  $b_3$  harmonics is set to 0 on purpose, the geometric aberrations generated by the 5 units of  $b_{3s}$  are well compensated by the  $\sim 90^\circ$  phase advance of the arc cell. Moreover, as far as the systematic  $b_3$  component of the main dipole field errors stays at 5 units and the variation of the arc cell phase advance is around  $1^\circ$ , the impact on the DA is negligible as shown by comparing blue dots with blue squares in Fig.6.

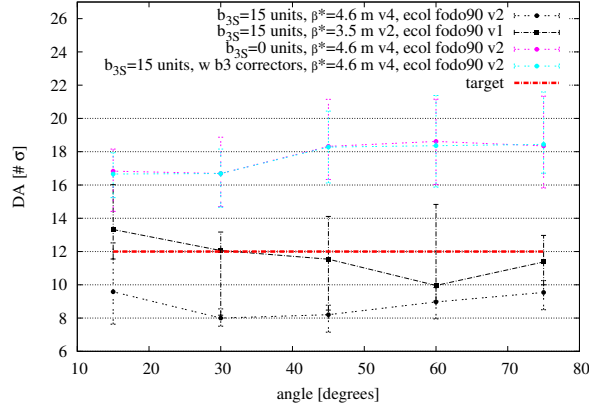


FIG. 7: Dynamic Aperture (DA) at the injection energy of 3.3 TeV in number of *r.m.s.* beam sizes as a function of the initial phase space angles, see text for details.

The black dots and squares in Fig. 7 represent DA computed with  $b_{3s}$  set to 15 units on purpose, in order to see visible effects on DA. In both cases the minimum DA is below the target value of  $12\sigma$  (i.e.  $\sim 8\sigma$ ). Not only the geometric aberrations generated by the  $b_{3s}$  are no more perfectly compensated by the arc cell phase advance, but the main sextupole integrated strengths, required to correct the chromatic aberrations, run at values well above the reach of present technology. Therefore, if the dipole field quality degrades due to persistent current at injection energy (up to 15 units of  $b_{3s}$ ), a local correction scheme is needed also at injection, namely spool pieces correctors attached to the main dipole, like in the LHC. Moreover,  $\sim 1^\circ$  difference in the phase advance of the arc cell and the different phases between the arcs start producing significant effects on DA ( $\sim 3\sigma$  on the average DA at  $15^\circ$ ), as shown by the black dots and squares in Fig. 7.

The light blue dots in Fig. 7 show that the 15 units  $b_{3s}$  are fully corrected using spool pieces correctors placed at each dipole of the arcs, correcting each the average  $b_3$  of the 8

arcs. Furthermore, the correctors strength effectively used for the correction is  $\sim 15\%$  of the maximum integrated strength that could be reached by present technology [11], leaving a lot of margin for correction.

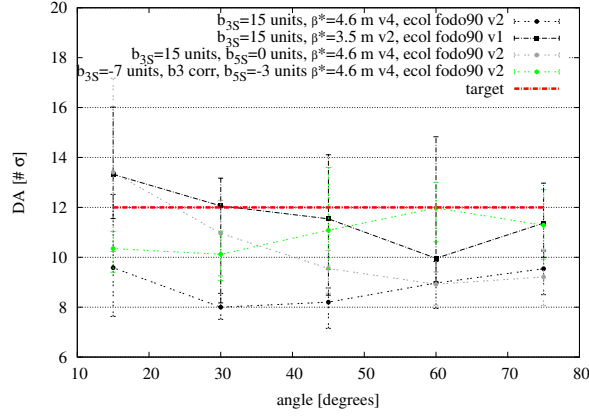


FIG. 8: Dynamic Aperture (DA) in number of beam  $\sigma$  as a function of the phase space angles explored for the baseline injection energy of 3.3 TeV, see text for details.

Finally, the impact on DA of 1 unit of  $b_{5s}$  can be seen by comparing the black dots with the grey dots in Fig. 8, where its value is artificially set to 0. This unit of  $b_5$  reduces the average DA of  $\sim 3\sigma$  at  $15^\circ$ , a similar impact is given by the  $1^\circ$  difference in the horizontal phase advance in the long arc cell (as shown by comparing the black dots and squares in Fig. 8). Moreover, with the correction of up to 15 units of  $b_{3s}$  the minimum DA is already above the target of  $12\sigma$ . If the  $b_5$  component turns out to be 3 times bigger than the value given in Table I, its impact on DA is not negligible anymore, as shown by the green dots in Fig. 8 and requires correction. In conclusion, if the systematic  $b_5$  component of the main dipoles errors stays strictly below 3 units, decapole correctors are not required for the present optics design.

## V. DETUNING AND TUNES SPREAD

Multipoles can drive tune shift for particles with energy or amplitude offset. The control of the fractional tunes is correlated to the dynamic aperture. In the LHC, the width of the stability island corresponds to  $\Delta Q = \pm 10^{-2}$ , i.e. for an induced tune shift of the order of or

bigger than  $10^{-2}$  a visible reduction of DA is expected. Detuning with amplitude and with momentum are faster and useful tools to complement DA calculations.

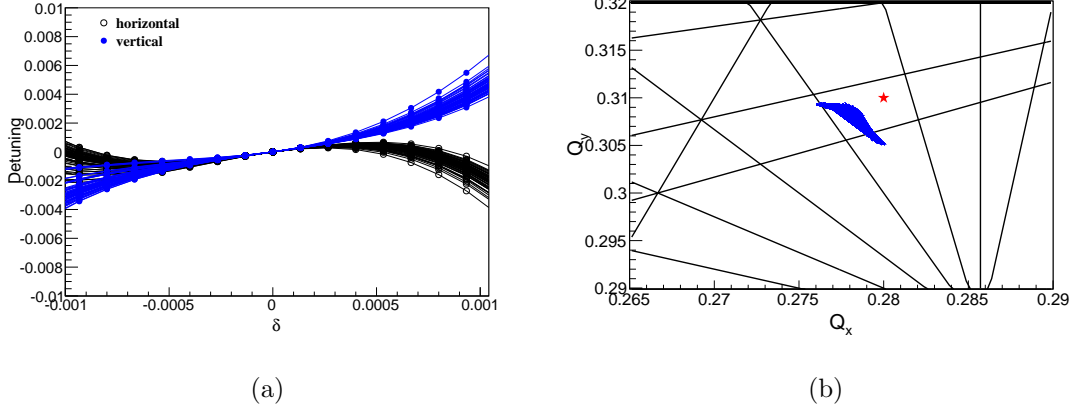


FIG. 9: Detuning with momentum (a) and with amplitude up to 7 beam  $\sigma$  (b) driven by the multipole error Table I, where  $b_{3s}$  has been set to 7 units and corrected with spool pieces (for the 60 seeds used in DA simulations). The lines show resonances up to the 9<sup>th</sup> order.

In Fig. 9 detuning with amplitude and momentum are shown in presence of the multipole field errors reported in Table I, with the only difference that the systematic component of  $b_3$  has been set to the target value of 7 (current target value) and corrected with the spool pieces. The chosen working point (the red star in Fig. 9) is well away from resonances of order  $\leq 5$ . The chromatic detuning is  $6 \cdot 10^{-3}$  for a maximum  $\delta p/p = \pm 10^{-3}$  and the detuning of particles with amplitude from 1 to  $7\sigma$  (collimator settings proposed for FCC-hh [8]) is  $\sim 5 \cdot 10^{-3}$ . The  $b_4$  and  $b_5$  multipoles errors are expected to impact the second and third order chromaticity [18], respectively. Figures 10 and 11 show the effect of the systematic component of  $b_5$  on the detuning with amplitude and with momentum, for different values of  $b_5$ . Comparing these tune shifts with the DA simulations, shown in Fig. 8, we see that a tune shift of  $0.9 \cdot 10^{-3}$  at  $\pm 10^{-3}$  gives visible effects on DA, as well as a detuning with amplitude of  $10^{-2}$ , thus they should be avoided. Therefore, a tolerance on the maximum  $b_5$  component of the field can be fixed to  $\leq 2$  units. Finally, the other components of the dipole field errors reported in Table I generate all together a tune spread well below the value  $10^{-2}$ , so they have a minor impact on DA.

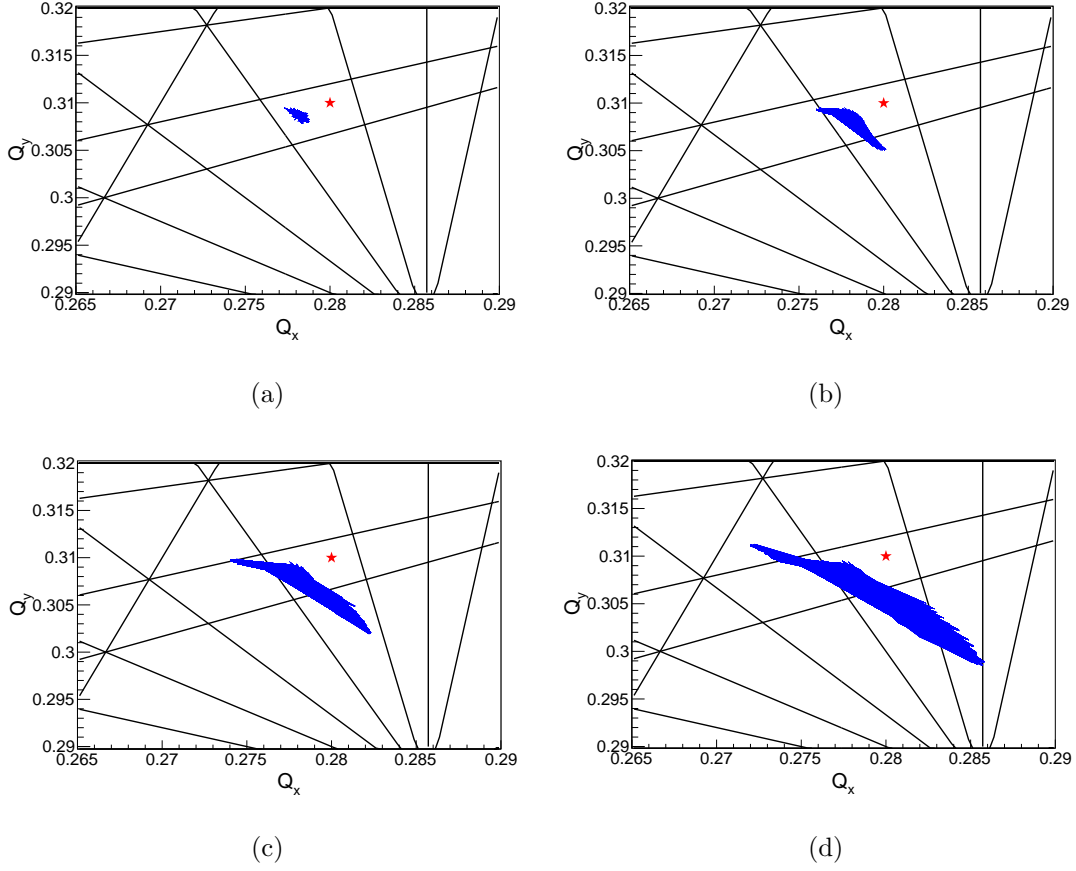


FIG. 10: Detuning with amplitude driven by the multipole error Table I, where  $b_{5S}$  has been set to 0 (a), to -1 (b), to -2 (c), and to -3 (d) units, for the 60 seeds used in DA simulations. The  $b_{3S}$  component is set to 7 units and corrected by spool pieces.

## VI. DISCUSSION

In this section further qualitatively considerations are given about the injection energy, about feed-down effect and about the impact of dipole type on DA simulations.

### A. Injection Energy

As far as DA is concerned, the present estimate of the field errors reported in Table I and also the new target value for the systematic component of  $b_3$  (7 units) at injection guarantee that DA is above the target of  $12\sigma$ . Considering that the ratio of DA at two different energies is equal to the ratio of the  $\sqrt{\gamma}$ , the lower limit for injection energy, as far as DA is concerned and using the present field quality table, is set to  $\sim 2.6$  TeV. In order

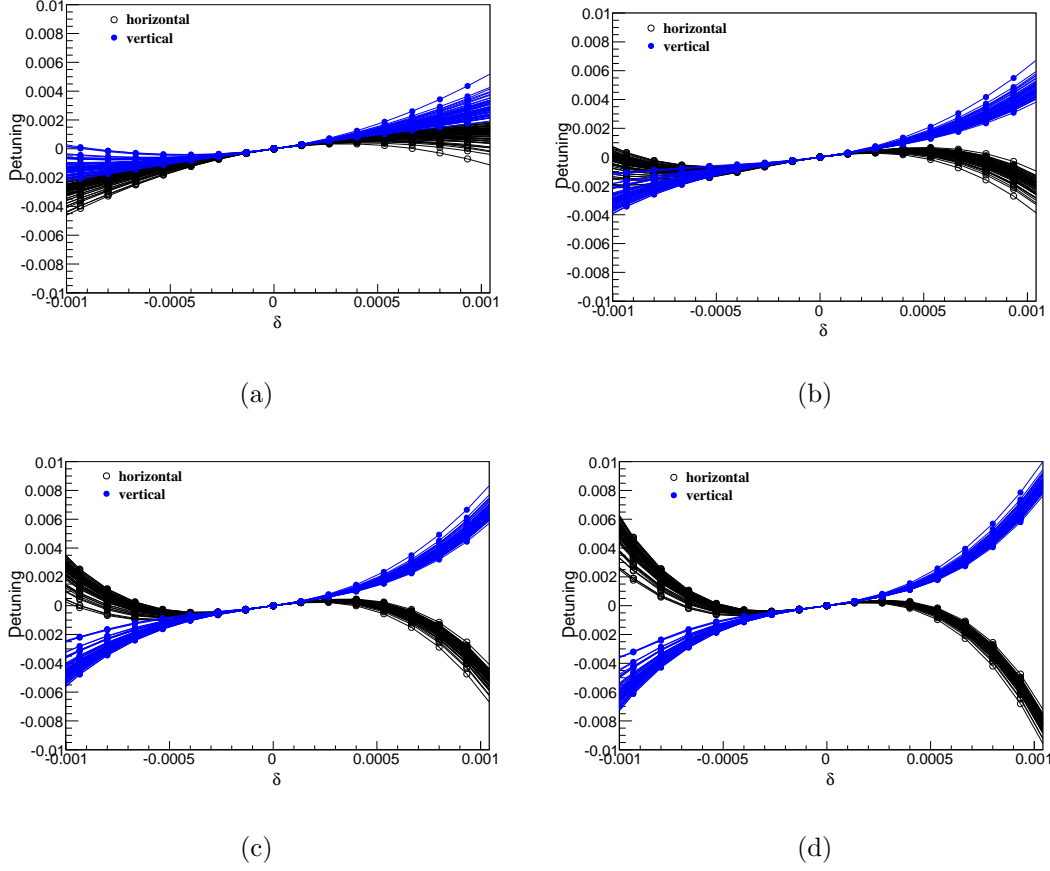


FIG. 11: Detuning with momentum driven by the multipole error Table I, where  $b_{5S}$  has been set to 0 (a), to -1 (b), to -2 (c), and to -3 (d) units, for the 60 seeds used in DA simulations. The  $b_{3S}$  component is set to 7 units and corrected by spool pieces.

to reach the 1.5 TeV proposed in [19] tighter tolerances on the random and uncertainty components of the main dipoles imperfections will be required to ensure the DA is above the  $12\sigma$  target value. Alternatively, a target for DA closer to the collimation settings limit ( $7\sigma$ ) should be considered.

### B. Feed-down effect

All tracking simulations showed in this paper do not take into account mis-alignment of the magnetic elements. This is expected to change the value of the multipoles shown in Table I due to feed-down effects of higher order multipoles on the multipoles of lower order. Following Ref. [14] the expected feed-down of  $b_3$  on  $b_2$  and of  $b_5$  on  $b_4$  due to position errors of main dipoles and spool-piece can be calculated analytically. Considering the same alignment

position errors reported in Table 8 of Ref. [14] one gets for the systematic component  $b_{2S}$ :

$$b_{2S}^{feed-down} = \pm 0.0141 \cdot b_{3S} \quad (3)$$

which corresponds to values between 0.099 and 0.211, taking  $b_{3S}$  equal to 7 or 15 units, respectively. For the random component of  $b_2$  one gets:

$$\sigma_{b_{2R}}^{feed-down} = \sqrt{0.0043b_{3S}^2 + 0.0058\sigma_{b_{3R}}^2} \quad (4)$$

which gives values between 0.46 and 0.98, taking  $b_{3S}$  equal to 7 or 15 units, respectively. In the case of 15 units the part of  $b_2$  due to feed-down becomes bigger than the estimated error due to the main dipole (0.481 units for both the  $b_U$  and the  $b_R$  component). These values should be added to the  $b_2$  of the main dipoles and will contribute to the  $\beta$ -beating, which impacts the mechanical aperture of the machine. Moreover, main quadrupole, main sextupole and straight section field errors and mis-alignment will also contribute to the  $\beta$ -beating and further reduce tolerances on acceptable total  $b_2$  and  $a_2$ , and as a consequence of  $b_3$ , coming from the main dipoles.

Always following Ref. [14] the systematic and random  $b_5$  feed-down on  $b_4$  is calculated as:

$$b_{4S}^{feed-down} = \pm 4 \cdot 0.0071 \cdot b_{5S} \quad (5)$$

$$\sigma_{b_{4R}}^{feed-down} = 4 \cdot \sqrt{0.0033b_{5S}^2 + 0.0015\sigma_{b_{5R}}^2} \quad (6)$$

which are equal to 0.028 units and 0.23 for the  $b_5$  component reported in Table I. These values of  $b_4$  are bigger than the components reported in Table I, thus they will have a non negligible impact on DA and can further reduce the tolerance on the  $b_5$  component.

### C. Dipole type

In all the simulations results presented here curved dipole (SBEND type) have been considered, and the multipole field expansion is done around the magnetic center of the dipole, which coincide with the reference particle trajectory. Due to the properties of the  $\text{Nb}_3\text{Sn}$  material, it has been proposed to build them straight (RBEND type). This implies that the reference particles does not travel always on the magnetic center of the element. The maximum beam excursion (the Sagitta  $x_S$ ) due to the dipole field is about 2.5 mm.

Therefore, assuming the multipole field expansion (of Eq. 1) is done always with respect to the magnetic axis. For a systematic offset equal to the Sagitta the maximum error on the  $b_3$  component of the field can be calculated using the same formula given for the feed-down harmonics (see Eq. (15) of Ref. [14]):

$$b_{3err} = b_5 \cdot 6 \cdot \left( \frac{x_s}{R_{ref}} \right)^2 = (b_{5S} + b_{5U} + b_{5R}) \left( \frac{x_s}{R_{ref}} \right)^2 \sim b_{5S} \cdot 0.13 = -0.13 \quad (7)$$

This value is less than the random component of  $b_3$  reported in Table I, which dominate the DA results as discussed in section IV. Moreover, considering that the multipole errors in the magnet are dominant at the magnet ends and almost zero at the longitudinal center of the magnet, the error on  $b_3$  is even less than the previous calculated value, if the beam is off-axis in the longitudinal center of the magnets. On the other hand the useful aperture of the beam will be reduced, therefore a balance should be found on the beam excursion along  $z$  in the magnet. Finally, in any case the error would be systematic for each of the dipole, thus the error on  $b_3$  would be corrected by the spool pieces.

## VII. CONCLUSIONS

The arc magnet specifications are reported and discussed in connection with the magnet group feedback. As far as the first estimate of the main dipole field quality is considered, the dynamic aperture of the current optics design of the future hadron-hadron collider is above the target value of  $12\sigma$  at injection energy (3.3 TeV). The current main dipole imperfections would allow to reduce injection energy to a minimum value of  $\sim 2.6$  TeV, as far as dynamic aperture is considered as criterion. The possibility to correct up to 15 units of the systematic  $b_3$  harmonics of the main dipoles is shown, leaving a lot of margin in the correctors strength at the injection energy of 3.3 TeV. A first tolerance on the  $b_3$  component is fixed to 7 units at injection but the feed-down effect on  $b_2$ , which impact the  $\beta$ -beating can further reduce this tolerance. No specification for the decapole correctors are given at this stage of the design and a tolerance to  $\sim 2$  units is fixed for the  $b_5$  component at injection, but first order feed-down of  $b_5$  on  $b_4$  can further reduce this tolerance. At collision energy the first estimate of the main dipole field quality strongly reduces DA (below  $10\sigma$ ). In particular, a new systematic value of the  $b_3$  harmonics (3 units) has been specified as target. Moreover, a minimum spool pieces integrated strength of a factor 2 higher with respect to



LHC is required. Further studies are needed to fully specify the main dipole field quality, in particular evaluate the impact on dynamic aperture of feed-down of the main harmonics due to mis-alignment errors.

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